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Macroeconomic impacts of climate change mitigation in Latin America: A cross-model comparison

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ABSTRACT

In this paper we analyse macroeconomic consequences of greenhouse gas emission mitigation in Latin America up to 2050 through a multi-model comparison approach undertaken in the context of the CLIMACAP–LAMP research project. We compare two carbon tax scenarios with a business-as-usual scenario of anticipated future energy demand. In the short term, with carbon prices reaching around \$15/tCO_2 by 2030, most models agree that the reduction in consumer spending, as a proxy for welfare, is limited to about 0.3%. By 2050, at carbon prices of \$165/tCO_2, there is much more divergence in the estimated impact on consumer spending as well as GDP across models and regions, which reflects uncertainties about technology costs and substitution opportunities between technologies. We observe that the consequences of increasingly higher carbon prices, in terms of reduced consumer spending and GDP, tend to be fairly linear with the carbon price in our CGE models. However, the consequences are divergent and nonlinear in our econometric model, that is linked to an energy system model that simulates step-changes in technology substitution. The results of one model show that climate policy measures can have positive effects on consumer spending and GDP, which results from an investment stimulus and the redistribution of carbon price revenues to consumers.

1. Introduction

This paper investigates the macroeconomic consequences of greenhouse gas (GHG) emission mitigation in Latin America. It is one of a series of model comparison papers that analyse baseline projections, technology pathways, land-use change, climate policy, energy supply investments, and other key aspects of future energy sector development and climate change mitigation in Latin America (van der Zwaan et al., 2016a,b). In addition, the series includes country-by-country cross-cutting papers emphasising important national circumstances relevant for climate change mitigation.

Macroeconomics is interrelated to the energy sector and the environment in many ways. The particular contribution of this paper is to offer insights on the range of expected economic consequences of climate change mitigation in Latin America as a whole as well as in detail for some of the region's major economies.

This paper first sets out the motivation for our work and the approach we followed including an overview of the key features and characteristics of the models involved in this analysis (Section 2). Section 3 discusses the model outcomes for the entire region of Latin America and for three individual countries in particular: Brazil, Mexico and Colombia. Section 4 highlights our key findings and conclusions.

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2. Motivation and approach

In its Fifth Assessment Report (AR5), as part of Working Group III, the Intergovernmental Panel on Climate Change (IPCC) investigates the impact of climate change mitigation. In particular, Chapter 6 (Clarke et al., 2014) assesses mitigation pathways and the economic costs of mitigation action. The evidence presented in AR5 represents the most comprehensive comparison of recent and relevant modelling studies and a synthesis of the model comparison literature. IPCC's AR5, Chapter 6, however, entails no specific results for Latin American countries and relatively little discussion of the Latin American region, which provides a strong motivation for our analysis presented in this paper

The AR5 evidence shows a significant variety of model estimates on the carbon price required to meet different atmospheric emission concentrations, as well as the impact of these carbon prices on gross domestic product (GDP) and consumption. The model results included in AR5 suggest that a carbon price between \$15/tCO_2 and \$200/tCO_2 (2010 prices) will be required in 2030 in order to achieve a long-term GHG concentration of 480–530 ppm CO_2 equivalent (CO_2e). According to AR5, this carbon price translates into a GDP loss between 0.2% and 4%. As the constraint on carbon increases in the scenarios assessed in AR5 over time, the carbon price increases exponentially, leading to the negative impact on GDP and consumer spending.

The results provided in AR5 reflect the energy system and macroeconomic modelling approaches available in the literature at the time of the IPCC's review. Of the scenarios assessed in AR5, 88 provide results for Latin America under a global emission concentration of 430–530 ppm CO_2e, and 87 provide results for Latin America under a global emission concentration of 530–650 ppm CO_2e. The results suggest that on average, mitigation costs in Latin America will be similar to the global average. However, the range of results is considerable. Some models report mitigation costs in Latin America being four times the global average, while others show hardly any mitigation costs for the region. Apart from the synthesis compiled by the IPCC AR5, macro-economic impacts of climate change mitigation have been studied for several world regions, including Latin America, by Bowen et al. (2013) and Tavoni et al. (2013), as well as for several Latin American countries, for instance for Brazil (Wills, 2013) and for the Chilean electricity sector (Benavides et al., 2015). Our study constitutes one of the first detailed multi-model scenario comparison analyses of the macroeconomic costs related to climate change mitigation in Latin America. Many of the models applied in our study have recently been expanded as part of the CLIMACAP–LAMP project to improve the coverage of Latin American countries.

2.1. Model coverage and scenarios

Seven macro-economic models are involved in our study, with a regional coverage as displayed in Table 1. The models' geographical coverage allows to compare modelling results for Latin America as a whole across five models, for Colombia and Mexico across three models, and for Brazil across five models.

To analyse macroeconomic interdependencies of climate change mitigation, this study focuses on the impact of different carbon prices relative to the development under a business-as-usual conditions. A set of common scenarios has been defined to frame the overall analysis for the CLIMACAP–LAMP project, of which we apply the following three scenarios to analyse macroeconomic consequences of carbon prices:

- Core baseline scenario: This business-as-usual scenario, gauged on baseline assumptions both on the regional and global levels, is used as the reference for all policy runs.
- Low CO_2 price scenario: A CO_2 price path scenario starting at \$10/tCO_2e[1] in 2020 and growing at 4%/year to reach \$32/tCO_2e by 2050.
- High CO_2 price scenario: A CO_2 price path scenario starting at \$50/tCO_2e in 2020 and growing at 4%/year to reach \$162/tCO_2e by 2050.

For more detailed descriptions of these scenarios, we refer to van Ruijven et al. (2016) and Clarke et al. (2016) for the Core baseline scenario and the two climate policy scenarios respectively. Van Ruijven et al. (2016) also provide detailed information on the model's base year calibration and the development of the main socio-economic parameters and energy indicators in the Core baseline scenario.

In accordance with the CLIMACAP–LAMP scenario framework, this study abstains from harmonising the model's baseline projections as well as assumptions on GHG abatement pathways and costs across models, and rather regards different assumptions on future technology and cost developments representative for the uncertainties of today's decision makers face (van der Zwaan et al., 2016a). This means for this analysis that the level of carbon emission abatement under a specific carbon price regime varies across models. We take this effect into consideration and report the emission reduction[2] associated with each scenario and model in the Results section. The strength of this approach is that the economic impact, which is defined relative to each model's baseline, can be compared meaningfully across models for each carbon price scenario.

2.2. Measures of economic cost

Relevant for our study is to identify appropriate measures for the quantification of macroeconomic costs that allow for a comparison of results across models. Paltsev and Capros (2013) outline alternative cost concepts for assessing impacts of climate change mitigation policy that are typically reported in macroeconomic modelling assessments:

- Carbon price
- GDP change
- Consumption change
- Welfare change.

All models applied in our analysis report GDP and consumer spending as measures of net economic cost. GDP is not a fully satisfactory indicator of cost because it focuses on the production of a country rather than the impact on consumers and can be distorted by changes in trade. Consumer spending measures domestic expenditures within a country and is therefore considered a crude proxy for consumer welfare. Although consumer spending only captures market activities and ignores non-market activities (which measures of welfare attempt to include), consumer spending is a reasonable proxy measure of welfare except under the following conditions:

1. If households increase their consumption to try to compensate for change in some circumstances. For example, although households spend more on heating in a colder year, they are not better off than during a warmer year.
2. If the increase in spending is financed out of savings or by higher borrowing, households are not better off even if spending is higher.

Table 1
Regional coverage of the models.

Model	Latin America	Brazil	Mexico	Colombia	Other Latin American countries/sub-regions
ADAGE	✓	✓			✓
E3ME–TIAM–ECN	✓	✓	✓	✓	✓
EPPA	✓	✓	✓		✓
IMACLIM–BR	✓	✓			
iPETS	✓				
MEG4C	✓			✓	
Phoenix	✓	✓	✓	✓	✓

[1] Unless stated otherwise, monetary units in this article refer to US\$(2005).
[2] All of the models report CO_2 emissions, with the exception of MEG4C which only reports GHG emissions, in CO_2e.

3. If the increase in spending has been achieved through a subsidy financed by government borrowing, this can be regarded as households borrowing from the future (because eventually taxes will have to be raised).
4. If the increase in spending is financed by lower company profits, households will eventually be affected through, for example, a reduction in the value of wealth held in equities (e.g., through pensions).

Welfare change, the fourth measure identified by Paltsev and Capros (2013), is not reported by all our models and is also difficult to observe in reality. Hence, welfare is not included as a measure in our study. The two main indicators of net economic cost for the paper are therefore GDP and consumer spending. The changes in GDP and consumer spending presented in our Results section reflect only the costs of reducing carbon emissions in response to the carbon price signal and thus ignore the economic impacts of climate change that are expected to occur if GHG emission concentrations continue to increase. Furthermore, none of the models include feedbacks that might arise from co-benefits of climate change mitigation, such as improved air quality from reduced pollutant emissions.

According to our scenario definition, carbon prices are model inputs, rather than outputs. By comparing the relative impact of a consistent carbon price across all models, it is possible to infer some meaning from the sets of model results without focusing on a comparison of baselines in each model.

Thus, the indicators compared to represent the total net macroeconomic consequences of climate change mitigation are as follows:

1. *The change in GDP relative to the change in carbon emissions*: to compare the net impact on economic activity arising from a carbon price with the net impact on CO_2 emissions.
2. *The change in carbon emissions relative to the carbon price*: to interpret the emission reduction potential in each model for the stated carbon price.
3. *The change in GDP relative to the carbon price*: to interpret and compare the impact of a carbon price on net economic output.
4. *The change in consumer spending relative to the carbon price*: to interpret and compare the impact of a carbon price on household consumption.

In addition to these four indicators the Results section contains the decomposition of the impact on GDP to better understand the differences between models. Therefore, we consider which components of GDP—consumer spending, investment, government spending or net trade (separated to imports and exports, if reported)—are most affected in the different models. Hence, for each region, we report and interpret five summary model outputs.

2.3. Overview of the models

Six of the seven models of our study belong to the category of computable general equilibrium (CGE) models, which explicitly model all sectors of the economy and their interaction, allowing to inspect both direct and indirect macro-economic effects related to climate policy. The remaining model (E3ME–TIAM–ECN) is a detailed macro-econometric simulation model (E3ME) soft-linked at the sector and country level with an energy system model (TIAM–ECN). Short summaries of each model are provided in the Supplementary material, while an overview of key characteristics of our CGE models is provided in Table 2. In the following two subsections we explain some of the main model features and their general implications on model results from a cross-model comparison point of view.

2.3.1. Cross-model feature comparison: comparing CGE models

Differences in economic cost across CGE models from imposing a carbon policy can largely be explained by differences in the model's ability to substitute to less carbon-intensive energy sources. As discussed in Clarke et al. (2014), five categories of model features determine the model's ability to shift to a less carbon intensive economy. First, models that capture the entire economic system could have higher economic cost related to climate policy than models which entail a subset only, because all sectors of the economy and their interactions are captured. On the other hand, the availability of more low-carbon options is likely greater in models that span over the whole economic system, which would contribute to reduce the total economic cost of climate policy.

A second determinant are the expectations in decision making. Models with myopic decision making (recursive dynamic) are likely to generate higher policy costs than models with inter-temporal decision making (perfect foresight) because models that optimise over time are able to more efficiently reduce emissions over the period of investigation.

Third, models that allow for trade across regions experience lower policy costs because abatement can occur where it is cheapest. Further, how models represent trade has implications as well. For instance, models that assume homogenous goods that trade at one world price (Heckscher–Ohlin) will have greater flexibility to substitute for less carbon-intensive goods than models that assume imperfect substitutability between domestic and imported goods (Armington).

Fourth, model assumptions regarding capital mobility have implications for the cost of carbon policies. The greater the mobility of capital,

Table 2
CGE model characteristics.

	Sector detail	Industry interactions	Representation of trade	Number of sectors traded	Capital and labour market flexibility	Foresight
ADAGE	36	Full set of inter-industry transactions	Armington with the exception of crude oil, which is treated as a globally homogenous good	36	Capital vintaging, limited labour and capital mobility between sectors	Recursive dynamic
EPPA	21	Full set of inter-industry transactions	Armington specification of trade for most goods except for crude oil and CO_2 permits, which are treated as homogenous goods	21	Capital vintaging in sectors with long-lived infrastructure; capital and labour mobile across sectors and regions	Recursive dynamic
IMACLIM–BR	19	Full set of inter-industry transactions	Import and export effects are modelled through elasticities calibrated for Brazil	19	Mobile capital; labour market: existence of unemployment and labour supply represented by a wage curve	Comparative-static
iPETS	9	Full set of inter-industry transactions	Armington	9	Mobile capital and labour	Perfect foresight
MEG4C	16	Industry is not disaggregated in the model	Armington	13 of 16 sectors are explicitly traded internationally	Capital is perfectly mobile; two types of labour: skilled and unskilled; structural unemployment rate of 10%	Recursive dynamic
Phoenix	26	Full set of inter-industry transactions	Armington except for crude oil and natural gas, which are modelled as homogenous goods	26	Capital and labour perfectly mobile	Recursive dynamic

the more flexible the model can shift away from carbon-intensive production with positive impacts on climate policy costs. Some models assume perfect capital mobility, and some models assume capital vintaging, where a certain portion of the capital stock is assumed to be fixed to the technology that it was allocated to originally, with little or no ability to be reallocated.

Lastly, sectoral, regional, and technology detail in the model also has implications for policy costs. On the far extreme, models with a single sector or region assume perfect substitutability across subsectors, whereas models with greater sectoral or regional detail do not. Therefore, policy costs could be higher the greater the model's regional or sectoral detail. Models with more technology detail are likely to generate lower policy costs if a larger pool of available low-carbon technology options exists.

As displayed in Table 2, most of the CGE models in our study capture the full set of inter-industry transactions, and most represent trade using the Armington substitution for energy carriers except, in some cases, for crude oil and natural gas. The biggest difference between the models is related to the respective assumptions regarding capital and labour mobility with some models assuming limited mobility, and others assuming perfect mobility.

2.3.2. Cross-model feature comparison: comparing E3ME to the CGE models

In terms of basic structure, purpose, and coverage, there are many similarities between the macro-econometric model E3ME and the CGE models of this study. Each is a computer-based economic model that considers energy economy environment (E3) interactions at the global level, broken down into sectors and world regions. The sectoral disaggregation is reasonably similar, although E3ME includes 42 sectors for non-European economies (69 for European economies) and is therefore more detailed in structure than the CGE models deployed. Both modelling approaches (CGE and macro-econometric) are based on a consistent national accounting framework and make use of similar national account data.

However, there are substantial differences in modelling approach, which has important implications on the interpretation of model results. The two types of model come from distinct economic backgrounds. Although both are in general consistent in their accounting and identity balances, they differ substantially in their treatment of behavioural relationships. Ultimately, this translates into assumptions about the economic actor's optimisation. The CGE models describe behaviour in line with economic theory; for example, they assume that individuals act rationally in their own self-interest and that prices adjust to market clearing rates. In this way, aggregate demand automatically adjusts to meet potential supply and output levels are determined by available capacity. As result of this optimisation assumption, all resources are fully utilised, and it is not possible to increase output and employment by adding regulation. Behavioural parameters (elasticities) in CGE models are the result of either an assumption on optimising behaviour or modeller judgement informed by the literature. In contrast, econometric models like E3ME interrogate historical data sets to try to determine behavioural factors on an empirical basis. The E3ME model is demand-driven, with the assumption that supply adjusts to meet demand (subject to any constraints). Typically, the supply–demand-equilibrium exists at a level that is likely below maximum resource capacity, leading to unemployment of available resources. In consequence, E3ME allows for the possibility of unused capital and labour resources to be utilised under the right policy conditions and, hence, additional regulation could lead to increases in investment, output, and employment.

In E3ME, the elasticities on trade are akin to Armington elasticities, which are estimated directly from the model time-series data for each country and sector. An exception to this are commodity markets, which follow the law of one price. Each of the sectors is able to trade. Investment in capital and the employment of labour are demand driven. The model solves on an annual basis which corresponds to a recursive dynamic algorithm in CGE terms. In this analysis, E3ME has also been soft-linked to the TIAM–ECN energy system model in order to enhance the technology variety within the context of a wider economic model.

3. Results

3.1. Latin America

Five models represent Latin America as an aggregate region. One of these (iPETS) models Latin America using aggregated data for the region, and the other four (ADAGE, EPPA, Phoenix and E3ME–TIAM–ECN) model some individual countries[3] as well as a catch-all “rest of Latin America” region. For these models, the results for Latin America are an aggregation of the results for the constituent countries and regions.

Fig. 1 displays for all five models the CO_2 prices of the two carbon tax scenarios and the corresponding CO_2 emission reductions versus the Core baseline emissions at different points in time (2020, 2030, 2040, and 2050). It can be observed that the levels of the achieved emission reductions vary across models and scenarios with emission reductions compared to the Core baseline between 3% and 36% at a CO_2 price of \$32/tCO_2 in 2050 and between 32% and 71% at a CO_2 price of \$165/tCO_2 in 2050. For the four CGE models, the results are linear and typically show (mildly) diminishing marginal abatement over time, while the results for E3ME–TIAM–ECN show signs of increasing marginal abatement in the Low CO_2 price scenario. This underlines a difference in the modelling approaches: it is increasingly difficult to substitute fossil fuels for clean energy in the CGE models, but TIAM–ECN's explicit representation of technology means that at given carbon prices, a new, previously uneconomical technology could replace an incumbent technology at scale. The relationship between carbon price and emission reduction in TIAM–ECN could therefore be non-linear and depends on the technologies available to the model which often relate to country-specific conditions of the energy system.

Fig. 2 shows the changes of GDP under the existence of carbon pricing compared to the Core baseline versus the achieved CO_2 emission reductions, and Fig. 3 illustrates the changes of the consumer spending for a given CO_2 price. In line with the variety of achieved emission reductions across models and scenarios, considerably different GDP impacts can be observed. In the Low CO_2 price scenario, each of the CGE models suggests that by 2030, at a carbon price of around \$15/tCO_2, emission reductions of between 6% and 20% can be achieved for a reduction in GDP of between 0.3% and 0.9% and a reduction in consumer spending between 0.3% and 0.5%.

In the longer term and at higher carbon prices, however, the bandwidth of the CGE model results increases, representing more uncertain about the future impact of carbon pricing. Of the four CGE models, ADAGE suggests a GDP impact of −3.6% for an emission reduction of 32%; EPPA suggests a GDP impact of nearly −5% for an emission reduction of 42%; iPETS suggests a GDP impact of −5% for an emission reduction of 70%; and Phoenix reports a GDP impact of −3% for an emission reduction of nearly 60%. For these four CGE models, the relationship between GDP and emission reduction is linear and fairly constant within each scenario.

The E3ME–TIAM–ECN results are starkly different from the CGE models. Although the reduction in emissions is similar, the change in GDP and consumer spending is positive. In addition, the E3ME–TIAM–ECN results are rather non-linear, reflecting the possibilities for technology substitution at different carbon prices reflected by TIAM–ECN. This difference in outcomes compared to the CGE models emanates from two counteracting effects in E3ME, which are caused by developments in the energy system. The structure of the energy economy changes

[3] ADAGE provides results for Brazil separately but not for other Latin American countries or sub-regions.

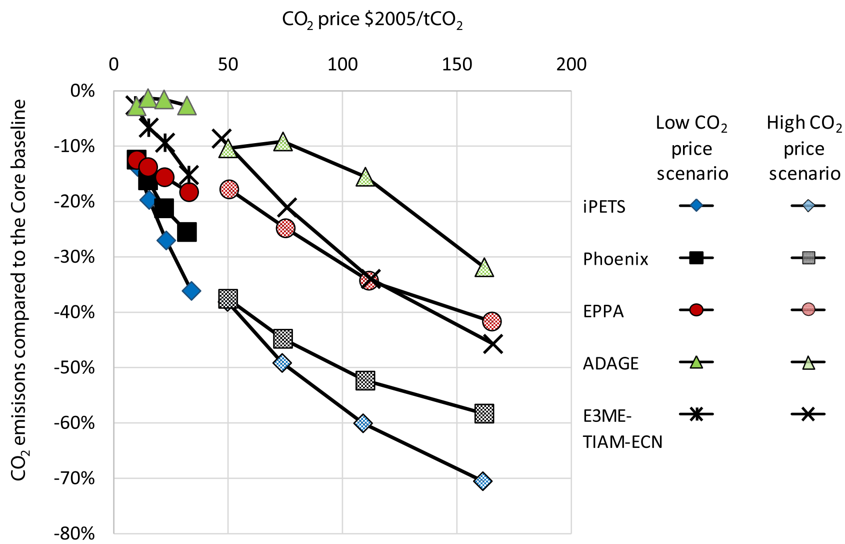

Fig. 1. Impact on CO_2 emissions for a given CO_2 price (compared to the Core baseline) in Latin America for the period 2020–2050.

from technologies with high fuel expenditures to more capital-intensive technologies, which requires increasing investments if climate policy is introduced. The higher investments in new technologies stimulate the economy, in particular the demand side, and outweigh economy-dampening effects emanating from higher energy prices for the period investigated. However, in the longer term (post 2050), consumers might still be paying for the investment stimulus that boosted the economy in earlier periods.

For the relationship between the CO_2 price and GDP (Fig. 4) we find two clusters of results among the CGE models, with EPPA and iPETS showing a similar development at higher negative GDP impacts than ADAGE and Phoenix. The E3ME–TIAM–ECN model approach diverges and shows a small but positive GDP impact in the long term.

Fig. 5 shows the decomposition of the GDP impact for each of the five models in 2050 in the High CO_2 price scenario. For E3ME–TIAM–ECN, an investment effect dominates the results. The investment is paid for, ultimately, by consumers, who see reductions in real household consumption. In net terms, GDP increases slightly because the shift in the structure of the economy, from fossil fuel supply chains to capital supply chains, leads to stronger dynamic multiplier effects that offset the reduction in GDP that comes about from the reduction in real income (and therefore real consumer spending) from higher prices.

ADAGE reports losses to consumer spending from the impact of higher consumer prices in the High CO_2 price scenario compared to the Core baseline. In consequence, this leads to lower output and lower investment and hence less government spending because government revenues are reduced. Moreover, exports are reduced following an overall loss in cost competitiveness. However, the reduction in demand for imports offsets this negative export effect in the trade balance.

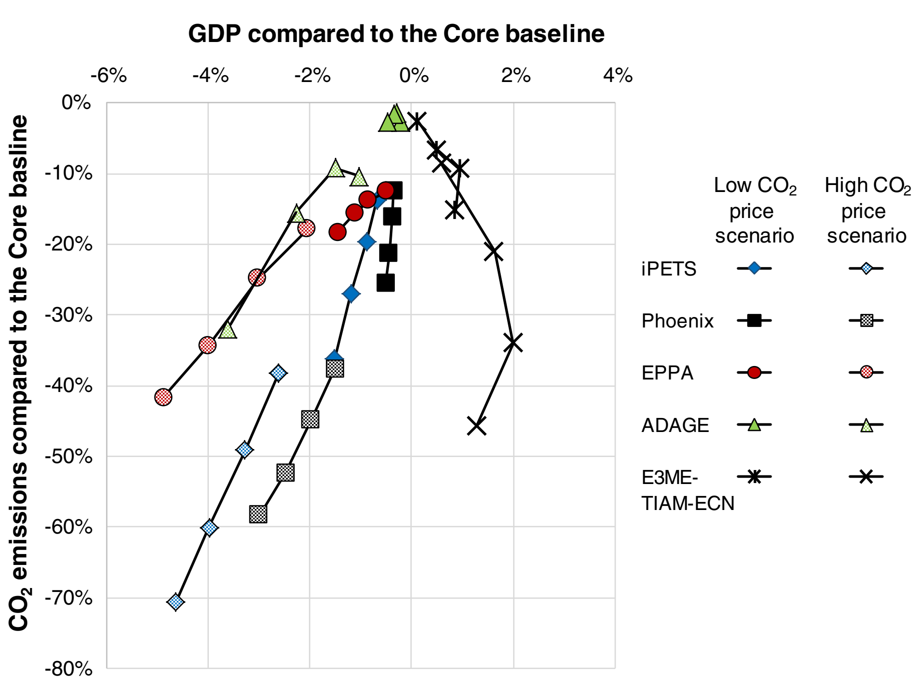

Fig. 2. GDP impact relative to CO_2 emission impact (compared to the Core baseline) in Latin America for the period 2020–2050.

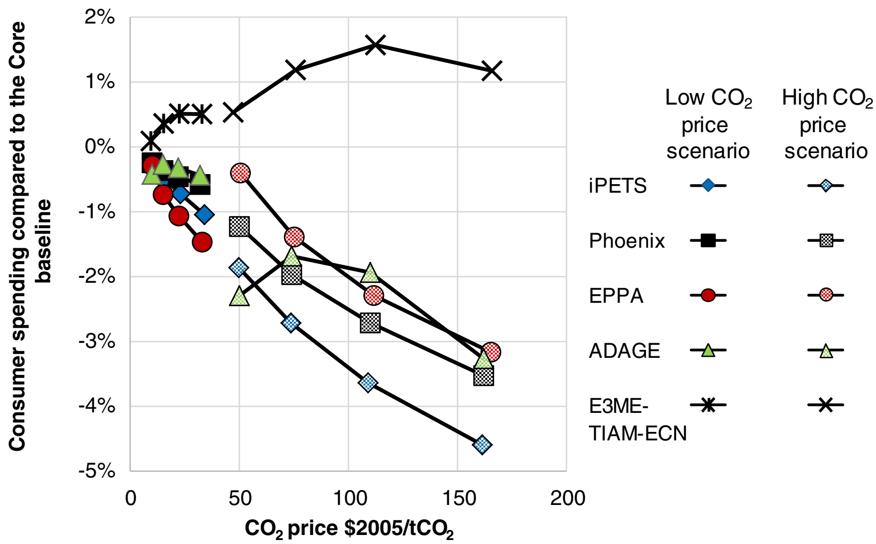

Fig. 3. Impact on consumer spending for a given CO_2 price in Latin America for the period 2020–2050.

iPETS results show that the GDP impact is mostly driven by consumer spending which declines by up to 3% in 2050 in the High CO_2 price scenario compared to the Core baseline. Reductions in revenues from exports cannot be outweighed by reduced imports, which results in a net negative trade impact under the high carbon tax regime until 2050.

Phoenix shows reductions in consumer spending, investment, and government spending. A small positive GDP impact resulting from trade can be observed, which suggests that Latin America exhibits a comparative advantage for some commodities under the High CO_2 price scenario. At the sectoral level, Phoenix reports for some of the Latin American regions an increase in the demand over time for coal, refined coal and oil products, and other heavy manufacturing reliant upon these energy goods. This result may sound counterintuitive, but although climate policy measures reduce the total demand for coal, regions that have extracted a smaller share of their resource base, as is the case with some of the Latin America regions relative to other exporting regions, experience a slower increase in production costs and prices. Thus, these regions and their trade partners are supplied with a relatively cheaper resource supply that is still in demand for some manufacturing and used in conjunction with carbon capture and storage for carbon-free electricity generation.

3.2. Brazil

For Brazil, we compare the macroeconomic results of five models: four multi-region models (ADAGE, E3ME–TIAM–ECN, EPPA, and Phoenix) and one single-region Brazil model (IMACLIM–BR).

The upper left panel of Fig. 6 shows the impact on CO_2 emission reductions for a given CO_2 price in Brazil. When carbon price starts at \$50/tCO_2 in 2020, the CO_2 emissions are reduced by 11% in E3ME–TIAM–ECN, 14% in ADAGE and IMACLIM–BR, 16% in EPPA, and 35% in Phoenix relative to the Core baseline scenario. When carbon price rises to \$75/tCO_2 in 2030, the CO_2 emission reductions remain stable in ADAGE at 14%, while emission reductions increase modestly in IMACLIM–BR and EPPA to 18% and 22% respectively. A strong decline of emissions can be observed for E3ME–TIAM–ECN with a reduction to 26% in 2030 and in Phoenix where emissions are 41% below the Core baseline scenario in 2030 in the High CO_2 price scenario. By 2050, at carbon prices around

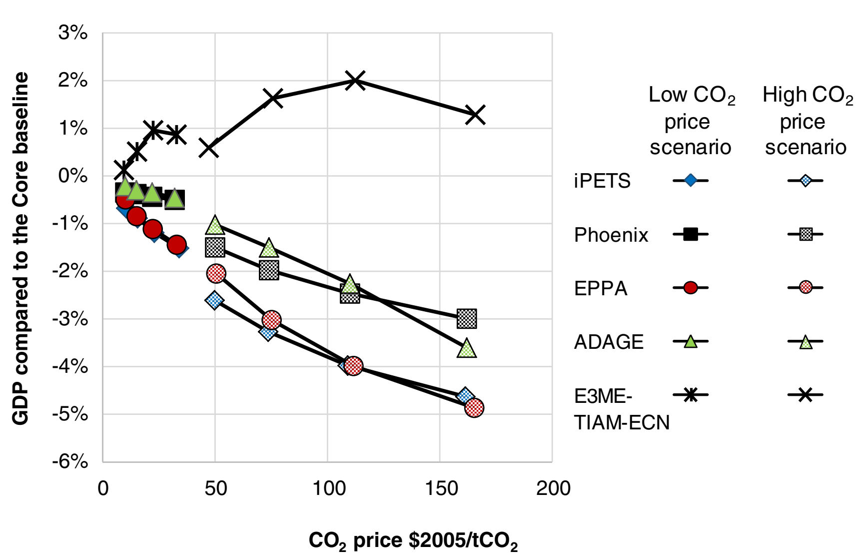

Fig. 4. Impact on GDP for a given CO_2 price (compared to the Core baseline) in Latin America in the period 2020–2050.

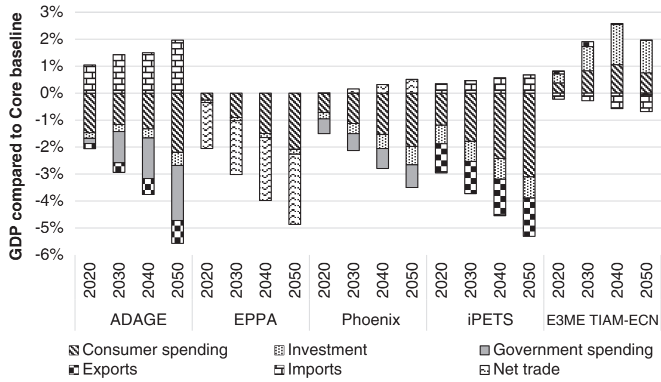

Fig. 5. Impact on GDP by GDP component in the High CO_2 price scenario in Latin America.

$165/tCO$_2$, the CO_2 abatement reaches a reduction versus the Core baseline of 30% in ADAGE, 31% in EPPA, 46% in E3ME TIAM–ECN, and 57% in Phoenix. E3ME–TIAM–ECN and Phoenix continue to exhibit the greatest reduction in emissions. The elasticity of CO_2 emission abatement and the details and type of technology that could be applied to reduce emissions are factors that can contribute to the difference of emission reduction among the CGE models. The change in relative emission reduction in E3ME–TIAM–ECN from 2030 to 2050 reflects the nonlinear characteristics of the TIAM–ECN energy system model, because climate change mitigation is modelled via cost–potential curves, which in total represent a non-linear relationship. Moreover, higher carbon prices can make new technologies, which are explicitly defined in TIAM–ECN, viable in economic terms, leading to step changes in the relationship between CO_2 prices and reductions in emissions.

The upper right panel of Fig. 6 shows the impact on GDP relative to CO_2 emission reductions from the Core baseline scenario. The ADAGE model displays a relatively smaller negative impact on GDP and smaller carbon abatement in the Low CO_2 price scenario than other CGE models. In the High CO_2 price scenario ADAGE and EPPA show a nearly identical pattern by 2050: a 30% reduction in CO_2 emissions would lead to a 2.1% reduction in GDP. The results for the IMACLIM–BR model seem to be on a similar trajectory to the ADAGE results, although the analysis only goes as far as 2030, at which point the IMACLIM–BR model reports a 1.9% GDP loss for an 18% emission reduction. In stark contrast, Phoenix suggests that Brazil could reduce carbon emissions by 56% by 2050 with a loss of only 2% of GDP. E3ME–TIAM–ECN exhibits an increase in GDP of 0.7% for a 46% reduction in CO_2 emissions.

The negative impact on the economy, as measured by GDP, is greater in EPPA than in ADAGE, IMACLIM–BR, and Phoenix when carbon prices grow from \$50/tCO$_2$ in 2020 at 4% annually (see the lower right panel of Fig. 6). By 2050, the impact of GDP at a carbon tax of \$165/tCO$_2$ reaches nearly the same level at −2% for all models except E3ME–TIAM–ECN. Like observed for the whole of Latin America, E3ME–TIAM–ECN shows a positive GDP impact in Brazil as well. However, at the lower-price scenario, the ordering of the relationship is different. For prices between \$10 and \$20/tCO$_2$, GDP falls by around 1% in IMACLIM–BR, by 0.5% in EPPA, by 0.25% in Phoenix, and by 0.2% in ADAGE.

The relationship between carbon price and consumer spending, the component of GDP most closely linked with welfare, is shown in the lower left panel of Fig. 6. For the consumption metric, Phoenix and IMACLIM–BR have stronger negative responses to carbon price than EPPA, while E3ME TIAM ECN and ADAGE show a positive response.

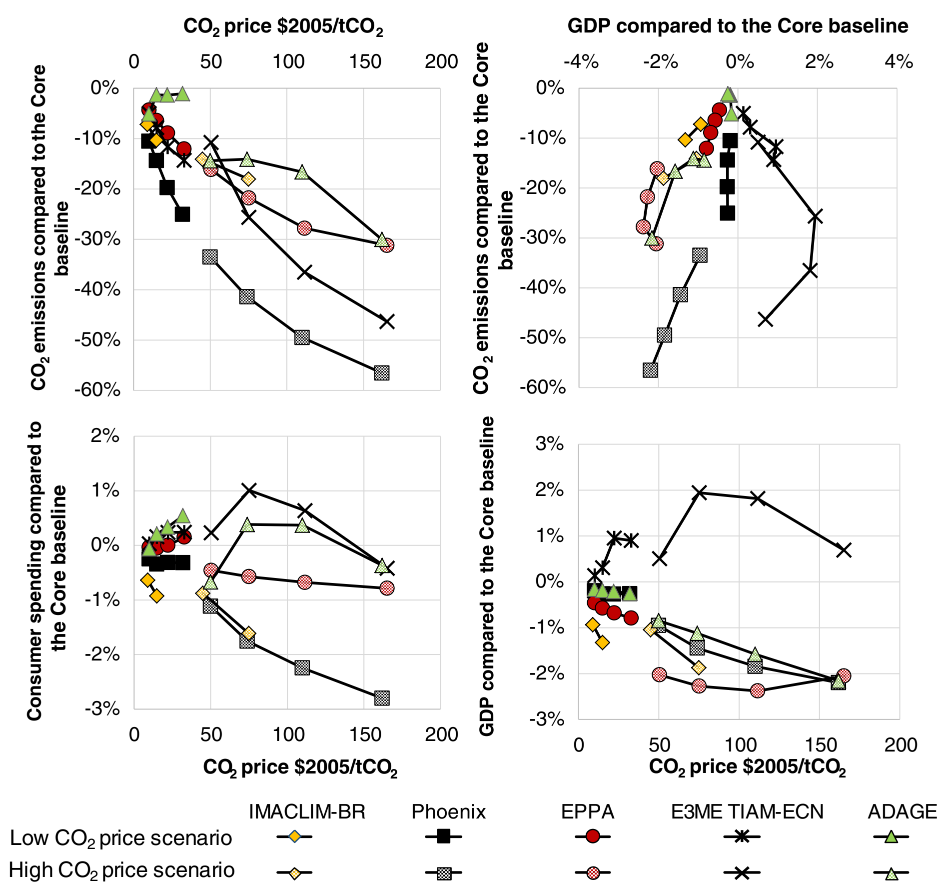

Fig. 6. Impact of carbon taxes on CO_2 emission reductions and related effects on GDP and consumer spending in Brazil for the period 2020–2050.

For example, at carbon prices of \$75/tCO_2 in 2030, consumption loss is between 1% and 1.75% for IMACLIM–BR and Phoenix, and only 0.6% for EPPA, whereas E3ME–TIAM–ECN and ADAGE see small increases in consumption of 1% and 0.4% respectively.

Factors such as consumer spending, government spending, investment, and trade are contributing to the GDP impact, but with different roles among models (see Fig. 7). Government spending in ADAGE plays a dominant role in the GDP loss. Despite small losses in GDP and consumer spending observed on IMACLIM–BR results, investments on mitigation measures induced by the carbon tax cause a small increase in overall investments in 2020 and 2030. For EPPA, net trade effects dominate the outcome, as price effects reduce the competitiveness of exports and of domestic goods and services relative to imports. By contrast, net trade in Phoenix makes a positive contribution to the GDP impact.

In E3ME–TIAM–ECN, additional investment in the power sector does not crowd out investment in the rest of the economy. Investment in productive assets is not constrained in the model; instead, the model assumptions implicitly describe a banking system which is able to provide additional financing, potentially (but not necessarily) by withdrawing from investment in non-productive assets or by further leveraging against capital assets. However, it is assumed that all investment is paid for (in full) by consumers and/or businesses, which may in turn pass on costs to consumers in the form of higher prices.

As a result, the impact on GDP in E3ME–TIAM–ECN is a net effect of the demand-side stimulus generated by increased real investment, increased prices reducing real consumption, and the net effects on the balance of trade. In principle, the positive investment impact could outweigh the negative price effects reducing real consumer spending because E3ME–TIAM–ECN allows for spare capacity of production factors and so demand-side stimulus can yield positive GDP results. Because many consumer goods are imported, the reduction in consumption leads to a reduction in imports, which also serves to partly offset the GDP impact (see Fig. 7).

3.3. Mexico

Mexico has made remarkable progress in terms of advancing national climate change policy. Although the country does not have binding emission targets under the Kyoto Protocol, the country has enacted legislation to reach aggressive emission reductions of 50% by 2050 and advanced the implementation of economic instruments, including a \$5 CO_2 tax on some fossil fuels. A comprehensive analysis of the results for Mexico, including a policy overview, can be found in Veysey et al. (2016).

Three models can be compared for Mexico: EPPA, Phoenix, and E3ME–TIAM–ECN (see Fig. 8). By 2020, for a carbon price of \$10/tCO_2e, Phoenix and EPPA find a reduction in consumer spending of 0.2% and 0.4%, respectively. As the carbon tax increases, both CGE models report increasing policy costs in terms of impacts to consumption. In EPPA, consumer spending in the Low CO_2 price scenario decreases compared to the Core baseline between 1.0% and 1.9% in 2030 and 2050, respectively. Phoenix estimates consumption loss between 0.2% and 0.3% for 2030 and 2050. E3ME–TIAM–ECN shows a positive impact on consumer spending of around 0.3% in the same years.

In contrast with the relatively modest changes in consumer spending in the Low CO_2 price scenario, the High CO_2 price scenario shows a wide range of possible impacts, both in terms of consumer spending and in terms of GDP. At a price of \$50/tCO_2 in 2020, GDP losses in EPPA and Phoenix are around 2%, while in E3ME–TIAM–ECN, this price leads to an investment-led economic demand stimulus (see the upper left panel of Fig. 8). EPPA and Phoenix report an increasing loss trend as the carbon tax increases further over time, with EPPA finding significantly higher losses than Phoenix. EPPA results show a total loss of consumer spending in the High CO_2 price scenario of 2% in 2030 and 5% in 2050, while Phoenix results reveal a decline of 1.4% and 2.8% in 2030 and 2050 for the same CO_2 price trajectory. Both of the CGE models agree on increasing consumption and GDP losses as carbon prices increase.

In contrast, consumer spending observed in E3ME–TIAM–ECN increases by 1% at a carbon price of \$110/tCO_2 in 2040, and decreases again by 0.5% by 2050. In this model, investment impacts lead to an increase in net economic output, which drives increases in real incomes. As a result of annualised investment accounting over the technology's economic lifetime, investments are not necessarily fully paid for by the end of the modelling period in the form of higher energy prices for the lifetime of the new capital good, if the lifetime exceeds the model horizon. This also means that economic costs and benefits do not necessarily take place at the same time.

As explained in Section 3 (and detailed in the Supplementary material), EPPA and Phoenix are both recursive dynamic CGE models with the capability of tracking global trade and energy flows in the economy. Both models assume similar growth rates (3.2% and 3.3% respectively as an average for the period 2005–2050) and compare well in their baseline trajectories. For example, EPPA estimates that Mexico's economy by 2050 will be \$3.6 billion in 2005 U.S. dollars, compared with

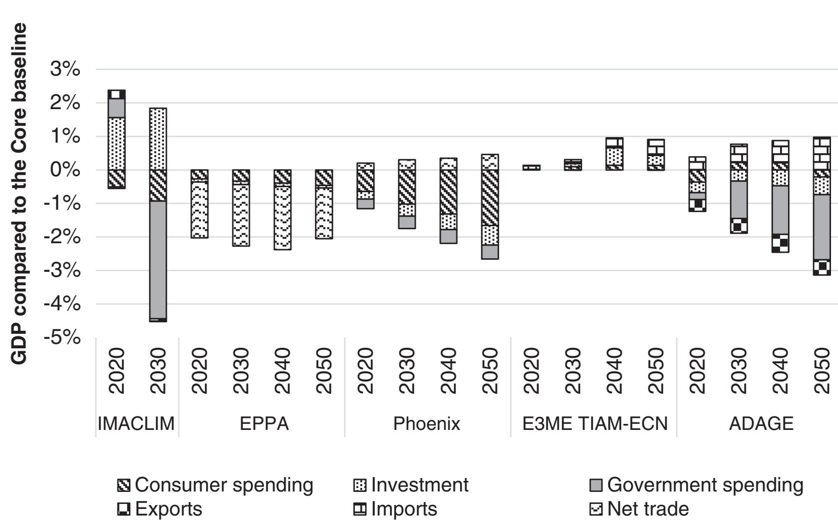

Fig. 7. Impact on GDP by GDP component in the High CO_2 price scenario in Brazil.

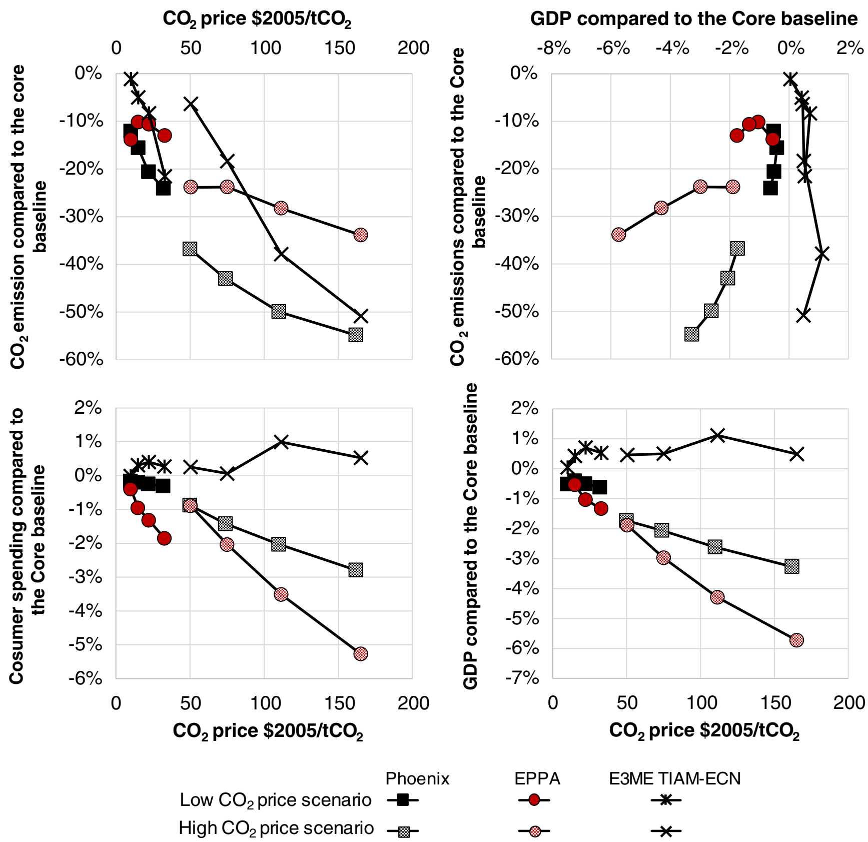

Fig. 8. Impact of carbon taxes on CO_2 emission reductions and related effects on GDP and consumer spending in Mexico for the period 2020–2050.

Phoenix's $3.8 billion estimate. However, the models diverge in total policy costs. First, the models have differences in baseline projections in both energy mix and other variables (van der Zwaan et al., 2016b). Importantly, Phoenix has higher baseline emissions than EPPA and often shows high abatement levels at lower carbon prices. Several parameter specifications can explain these deviations in total policy cost:

- the vintage structure for capital (EPPA includes capital vintage to account for investment in long-lived assets in some sectors of the economy, such as the power sector and, to some extent, the refined oil sector and energy-intensive industries);
- different structures of the production functions for electricity, which influences the substitution between different technologies within the sector;
- detailed CO_2 and other GHGs modelling in EPPA, including land-use changes; and
- specifications of resource endowments, which affect total oil trade.

In addition, the malleability of capital is an important difference between the two models. Abandoning investments in the power sector of infrastructure that has not been depreciated is costly in the EPPA model, reflecting the fact that there is a social cost of sunk capital in some industries. Both models agree on negative impacts from the shift of trade patterns under a global carbon tax regime because Mexico is an oil-exporting country that is affected not only by the implementation of climate policy in the country but also by a global shift to low-carbon technologies and hence reduced demand for fossil fuels. In summary, differences in the macroeconomic impacts between models can be explained by changes in total consumer expenditure resulting from different prices of energy and other goods and services in the economy, as well as terms of trade effects, that affect Mexico's oil exports.

In the case of E3ME–TIAM–ECN, the long-term positive net impact on GDP mostly reflects two competing factors which are driven by the changing structure of the energy system. When high carbon taxes are introduced fuel-intensive technologies are substituted by capital-intensive technologies which provide an investment stimulus. The technology outcome matters considerably in the determination of the E3ME–TIAM–ECN results, particularly in the overall cost and the relative weighting of the capital and operating cost components and the characteristics of those supply chains in the domestic economy. Until 2040, the investment effects dominate, however, these become less important by 2050 (see Fig. 9). In the High CO_2 price scenario, E3ME–TIAM–ECN experiences a negative net trade effect, in particular in the long run with up to 0.7% (2040) reduction of GDP compared to the Core baseline scenario.

3.4. Colombia

For Colombia, the implementation of a carbon tax regime may impose macroeconomic costs, as reported by the two CGE models MEG4C and Phoenix, or positive macroeconomic effects, as shown by E3ME–TIAM–ECN (Fig. 10). Results from the two CGE models reveal that Colombia's GDP in 2050 would be between 2.3% and 2.9% lower compared to the Core baseline scenario if a global carbon tax as high as $165/tCO_2$ is implemented. By contrast, E3ME–TIAM–ECN shows that Colombia's total net GDP impact could be positive, with an increase of 3.0% in 2050 in the High CO_2 price scenario compared to the Core baseline.

Despite similar MEG4C and Phoenix results on GDP impacts, abatement calculated by each model is very different, as depicted in the upper left panel of Fig. 10. While MEG4C estimates that emissions would decrease by 7% by 2050 at a price of $165/tCO_2$, Phoenix presents for the same year and carbon price a reduction of almost 60% relative to

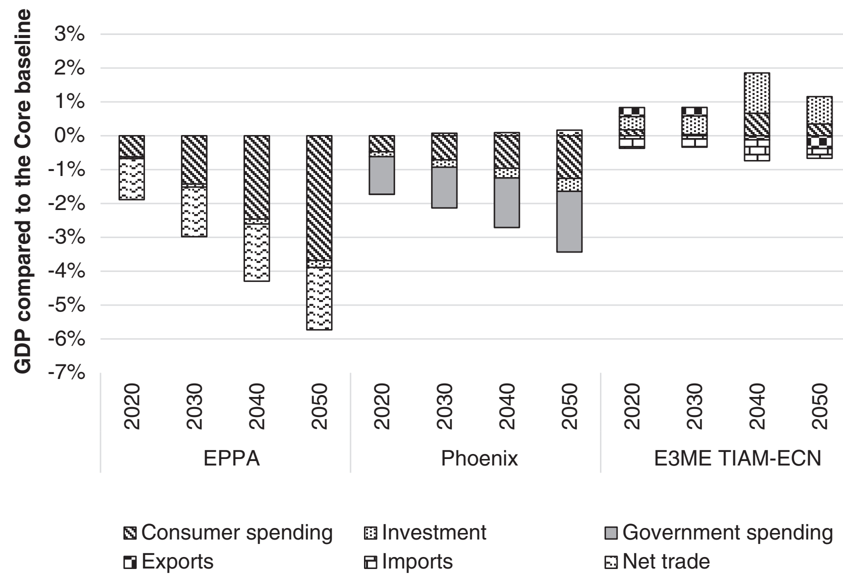

Fig. 9. Impact on GDP by GDP component in the High CO_2 price scenario in Mexico.

the Core baseline scenario. MEG4C's low abatement response is due to the fact that very few low-carbon technologies are available in the model, and abatement is mainly achieved through reduced economic activity instead of adoption of cleaner technologies. On the contrary, according to Phoenix, carbon taxes in Colombia achieve high levels of abatement through a combination of lower economic activity and substitution towards low-carbon inputs and technologies, which could include the deployment of technologies put forward by in-country researchers (Calderon et al., 2016), such as coal and natural gas technology with CO_2 capture and storage (CCS) for electricity production after 2035.

In line with the differences between models on the total macroeconomic effect of climate policy, the models show that consumer spending could be either reduced in the High CO_2 price scenario compared to the

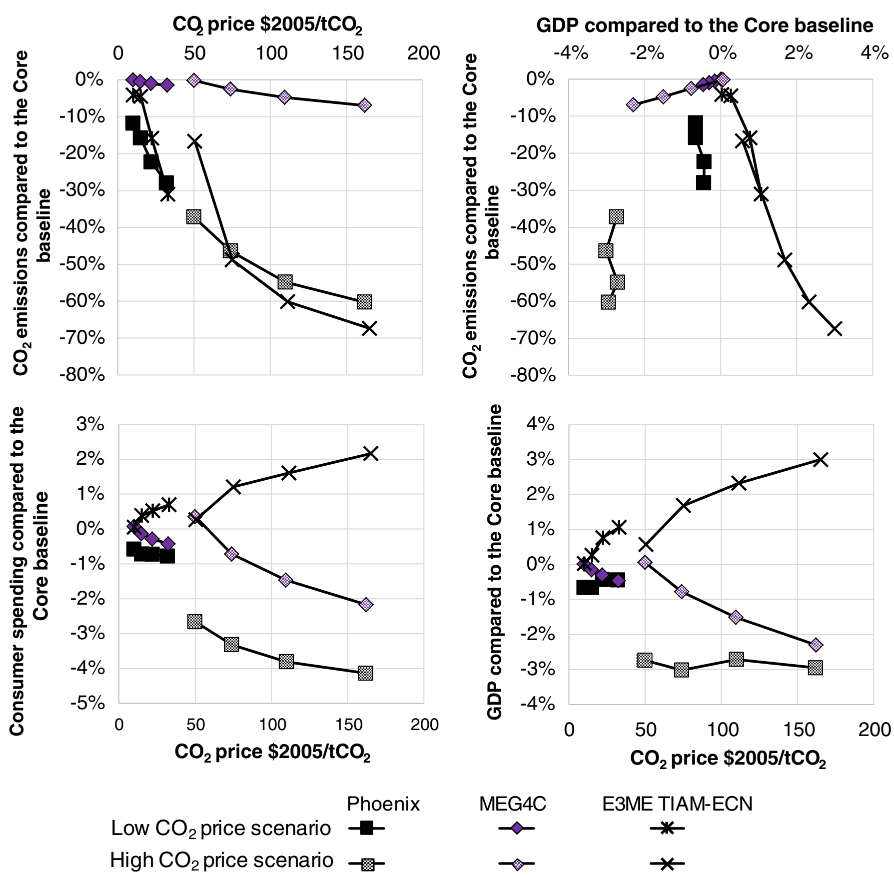

Fig. 10. Impact of carbon taxes on CO_2 emission reductions and related effects on GDP and consumer spending in Colombia for the period 2020–2050.

Core baseline scenario, as observed for Phoenix (−4.1% in 2050) and MEG4C (−2.2% in 2050) (lower left panel of Fig. 10), or increased, as seen for E3ME–TIAM–ECN where consumer spending is 2.2% higher in 2050 if the carbon tax regime is introduced. In general, carbon taxes increase the prices of energy and carbon-intensive goods such as transportation, manufacturing, and electricity. Because the level of substitution between goods is low for private consumption, final demand decreases. Phoenix shows the highest impact, which is consistent with lower elasticity of substitution in private consumption function. MEG4C projects an increase in consumer spending in 2020 as tax revenues are recycled back to households in the form of transfers, thus stimulating final demand; however, the impact of such stimuli fades under higher carbon prices.

As consumer spending contributes to more than 60% of GDP in both MEG4C and Phoenix, the impact of carbon tax on consumption drives most impacts on total output in the High CO_2 scenario (see Fig. 11). However, in both CGE models, investment also declines as a result of lower levels of savings in response to dampened economic activity. The opposite dynamic can be observed for the E3ME–TIAM–ECN model which shows an investment stimulation, outweighing the impact of higher prices under climate policy. Higher investments in the High CO_2 price scenario compared to the Core baseline and no crowding-out of long-term full employment lead to growing real incomes and increased consumer spending.

In terms of international trade, Phoenix presents a changing pattern of net trade impacts over time. Compared to the Core baseline a negative impact on net exports is induced in the High CO_2 price scenario in 2020 and 2030 whereas in 2040 and 2050 net export impacts become positive. For the period until 2030, a significant impact emanates from reduced exports of fossil fuels under the carbon tax scenario, in particular coal, which declines in this period by 40–50% compared to the Core baseline. In 2040 and 2050, however, Colombia's coal exports in the High CO_2 price scenario increase the export levels of the Core baseline as trade partners increase the use of CCS in electricity generation. Under the climate policy scenario, total cumulative coal production is lower as well as extraction costs. Therefore, coal is less expensive in relation to the Core baseline scenario. Lower-priced coal makes coal-intensive industries, like iron and steel production, more competitive, which drives a slight increase in iron and steel exports as well, deepening the positive long-term effect on net exports in the High CO_2 price scenario. In E3ME–TIAM–ECN, increasing imports and decreasing exports in the High CO_2 price scenario compared to the Core baseline partly offset the positive impacts on investment and consumer spending. In this regard, shifts in coal trade support this development with 40% reduction of Colombian exports over the period 2020 to 2050 in the High CO_2 price scenario compared to the Core baseline.

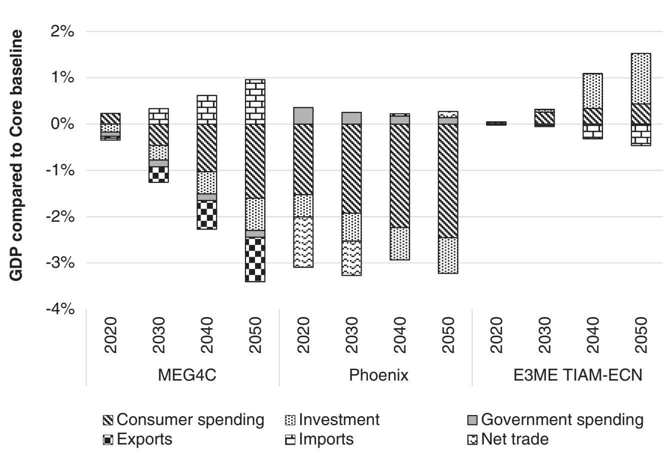

Fig. 11. Impact on GDP by GDP component in the High CO_2 price scenario Ein Colombia in 2050.

Table 3
Cross-country result comparison for the High CO_2 price scenario and for the year 2050.

	Latin America	Brazil	Mexico	Colombia
Number of models	5	5	3	3
CO_2 price ($/t$CO_2$)	165.0	165.0	165.0	165.0
Emission change				
Average CO_2 reduction (%)	−50%	−41%	−47%	−45%
Largest CO_2 reduction (%)	−71%	−57%	−55%	−67%
Minimum CO_2 reduction (%)	−32%	−30%	−34%	−7%
GDP change				
Average GDP change (%)	−3%	−1%	−3%	−1%
Maximum decrease in GDP (%)	−5%	−1%	−6%	−3%
Maximum increase in GDP (smallest decrease) (%)	1%	*−1%*	0%	3%
Consumption change				
Average consumption change (%)	−3%	−1%	−3%	−1%
Maximum decrease in consumption (%)	−5%	−3%	−5%	−4%
Maximum increase in consumption (smallest decrease) (%)	1%	*0%*	1%	2%

3.5. Cross country comparison

By comparing the model results across regions, some common observations can be made as displayed in Table 3 for the High CO_2 price scenario.

For the Latin America as a whole and its two largest economies, Brazil and Mexico, the following conclusions can be drawn:

- An emission reduction of between 30% and 70%, with a simple average of between 40 and 50%, is expected by 2050 at carbon prices of $165/t$CO_2$.
- The impact on GDP through an ambitious CO_2 price regime and recycling the revenues back to consumers is expected to be between −6% and +1% by 2050.
- This is equivalent to reducing the annual average GDP growth rate by between −0.08 and 0.04 percentage points (pp).
- The impact on consumer spending is expected to range between −5% and +1% by 2050.

For Colombia, the economic impacts of CO_2 pricing are broadly in line with those of the other countries modelled. The range of results in terms of achieved emission reductions, however, is much wider (7% to 67% by 2050), which reflects uncertainties regarding Colombia's technical capabilities to reduce GHG emissions.

4. Conclusions

This paper presents a first detailed multi-model scenario comparison analysis of the macroeconomic costs of decarbonising the Latin American economy through carbon pricing. The scenarios that we inspected can only be considered as illustrative: CO_2 pricing and simple redistribution of CO_2 price revenues to consumers define the scenarios to simplify the model comparison exercise. A more in-depth analysis of individual countries and regions, and country-specific policy tools, such as regulation, fiscal instruments, national revenue recycling schemes and trade policy, could provide more policy-relevant outcomes, but at the cost of consistency across models.

The following key findings have emerged:

- In the short term, if carbon prices reach around $15/t$CO_2$ by 2030, our CGE models agree that the reduction in consumer spending (as proxy for welfare) is limited in all Latin American countries that we modelled as well as across the continent (between 0.1% and 1%, with an average of 0.3%).

- By 2050, at carbon prices of \$165/tCO_2, there is much more divergence in the estimated impact on GDP and consumer spending across models and regions, which reflects uncertainties about technology costs and substitution opportunities between technologies
- In the E3ME–TIAM–ECN approach, the impact of carbon pricing on consumption and GDP can be positive because the investment stimulus (in new technology required to reduce carbon emissions) and the redistribution of carbon price revenues to consumers outweighs the consumption losses as a result of higher prices.
- Consumer spending and GDP decrease fairly linearly with growing CO_2 prices in the CGE models, whereas the opposite dynamic can be observed for the E3ME–TIAM–ECN model with a rather non-linear relationship. This non-linearity results from step-changes in technology substitution in TIAM–ECN and the impact of each technology (its cost, cost composition and supply chain implications) as represented in E3ME.

The finding that the macroeconomic cost of abatement can vary across models is consistent with the IPCC report finding that differences in economic cost across CGE models from imposing a carbon policy can largely be explained by differences in the model's ability to substitute to less carbon-intensive energy sources (Clarke et al., 2014). Comparing our results on GDP impacts in Latin America with the findings of the IPCC AR5, which reports GDP loss on the global level, reveals that the minor GDP impacts we observe under moderate carbon taxes in the mid-term are in line with the median of cross-model results of about 0.3% GDP loss in 2030 under a carbon price of around \$20/tCO_2 (Clarke et al., 2014). For the year 2050, the IPCC AR5 shows a range[4] for global GDP loss between 1.5% and 3% at a carbon price range of about \$80–200/tCO_2 (Clarke et al., 2014). In comparison, the GDP impacts as determined in our analysis for Latin America under a carbon tax of \$165/tCO_2 in 2050 ranges from −5% to 1% across all models. Reasons for this difference to IPCC can be manifold, such as the inclusion of regional particularities or differences in the methodology to determine GDP impacts. For the models involved in our study, we find that in comparison to the CGE models, the E3ME–TIAM–ECN model largely yields divergent macroeconomic impacts because of fundamental differences in economic structure and model approach that allow policy intervention that stimulates the demand side to lead to positive impacts on GDP. The outcome in E3ME–TIAM–ECN that consumer spending could be increased suggests that the price influences resulting from more-expensive (low carbon) energy do not outweigh the macroeconomic impacts induced by structural changes to the energy system.

Overall, the model results suggest that countries in Latin American can expect to see limited impacts on consumer spending and GDP in the medium term with carbon prices of around \$15/tCO_2. For the long term perspective, modelling results present a modest range of the potential macro-economic impact of carbon taxes up to \$165/tCO_2.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2016.02.002.

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[4] The ranges refer to the 25%/75% percentile. The total range for global GDP loss spans between almost zero and 10%. These results correspond to the group of scenarios achieving a long-term greenhouse gas concentration of 530 − 580 ppm CO_2eq (Clarke et al., 2014).